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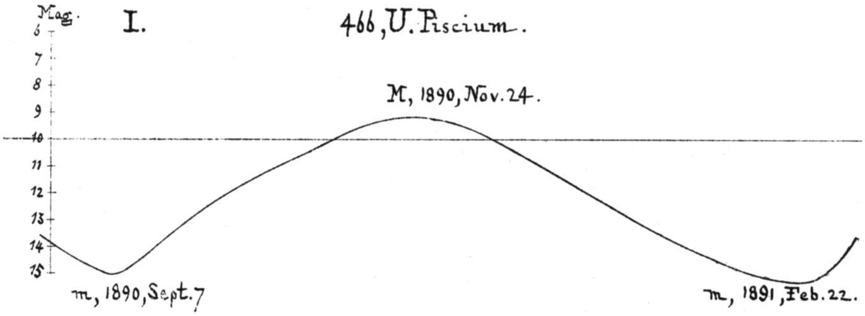
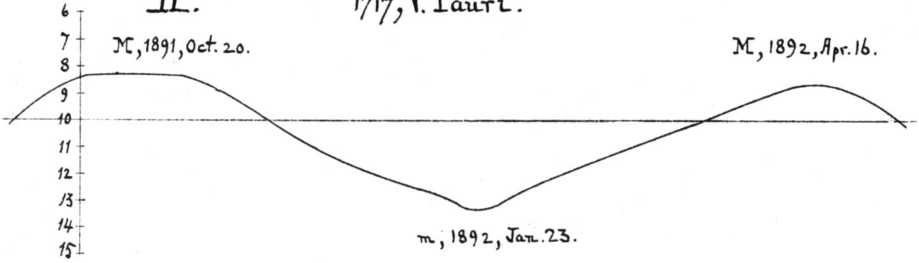
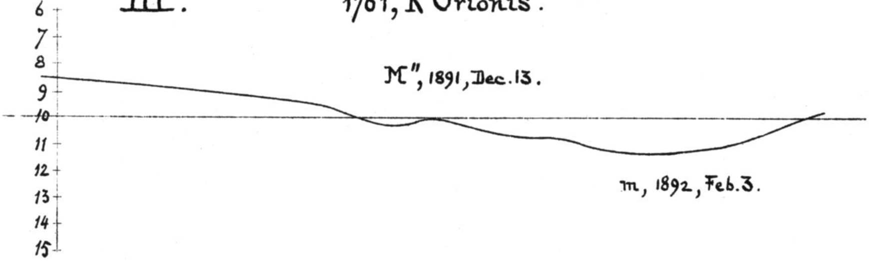
I. 466, U. Piscium.



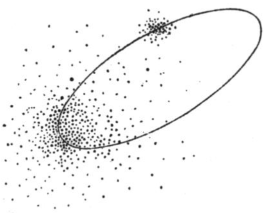
II. 1717, V. Tauri.



III. 1761, R Orionis.



IV.



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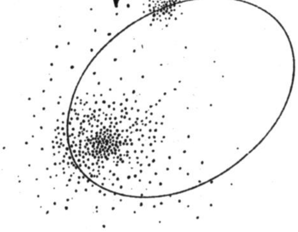
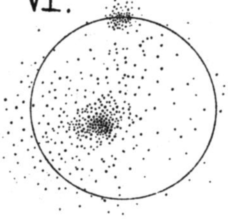


VI.



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VARIABLE STARS OF LONG PERIOD.

BY S. D. TOWNLEY, M. S.; HEARST Fellow in Astronomy, LICK Observatory.

In order to study the phenomena of variable stars numerous classifications have been proposed, but the most complete and the one now most generally used is that of Professor EDWARD C. PICKERING, Director of the Harvard College Observatory.

The classification is as follows: *

"I. Temporary stars. Examples: Tycho Brahé's star of 1572, new star in Corona, 1886; [also *Nova Aurigæ*, 1892].

"II. Stars undergoing great variations in light in periods of several months or years. Examples: *o Ceti* and *χ Cygni.*

"III. Stars undergoing slight changes according to laws as yet unknown. Examples: *α Orionis* and *α Cassiopeiæ.*

"IV. Stars whose light is continually varying, but the changes are repeated with great regularity in a period not exceeding a few days. Examples: *β Lyræ* and *δ Cephei.*

"V. Stars which every few days undergo for a few hours a remarkable diminution of light, this phenomena recurring with great regularity. Examples: *β Persei* (Algol) and S *Cancri.*"

The second class, stars undergoing large variations of light in periods of several months, or variable stars of long period, forms the subject of discussion in this paper. Stars having periods of more than fifty days fall into this class, and those having periods of less than fifty days come under either the fourth or fifth class. This line of division is not entirely arbitrary, for the long periods are mostly greater than three hundred days, and the majority of short periods are less than twenty days.

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* Proc. Amer. Acad. xvi, I.

LENGTH OF PERIOD. CHANDLER'S Catalogue of Variable Stars (1888) contains one hundred and thirty-two stars that belong to the long period class. The shortest period is sixty-five days, and the longest seven hundred and thirty days, but between these limits the stars are not uniformly distributed, as the following table will show:

Period.—Days.	Number.	Per Cent.
50—100	5	3.8
100—150	6	4.6
150—200	10	7.6
200—250	16	12.1
250—300	20	15.2
300—350	30	22.7
350—400	24	18.2
400—450	12	9.1
450—500	5	3.8
500—550	0	0.0
550—600	1	0.8
600—650	1	0.8
650—700	0	0.0
700—750	2 *	1.5
Total	132	100.1

* My observations show the period of 5430, T *Libræ*, to be 244 days rather than 723 days, as given in CHANDLER'S Catalogue. The period of 5688, R *Libræ*, given as 730 days, is very uncertain, so that the longest period yet determined with certainty is that of 432 S *Cassiopeæ*, 607.5 days.

This table shows that periods of about a year largely predominate, forty-one per cent. of all being between three hundred and four hundred days. The mean of the periods, excluding those of T *Libræ* and R *Libræ*, is three hundred and three days. A graphical representation of the data set forth in the table shows that the distribution of periods is very closely represented by GAUSS' error curve; and this, together with the fact that the highest point of this curve corresponds to periods of about a year in length, cannot be looked upon as entirely fortuitous and are two important points that must be kept in mind by him who would attempt to formulate a theory to explain this kind of stellar variability.

Variation of Period. The length of period in stars of this class is usually not constant. If two maxima of a star have been observed and its period thus determined, it is quite probable that future observations will show deviations from this period amounting to several days or weeks, so that the period derived will need to be corrected by some secondary term.

If the recurrences are perfectly uniform then the time of any maximum or minimum can be computed from the equation,

$$T_1 = T_0 + PE,$$

in which T_0 is an observed time of maximum or minimum, P the period of variation and E the number of periods passed through since the time T_0. If, however, the period of the star is increasing or decreasing, then the equation will be modified to the form,

$$T_1 = T_0 + PE + cE^2,$$

in which c is a constant to be determined from the observations, positive if the period is increasing and negative if the period is decreasing. As the number of observations is increased, perhaps the third and fourth powers of E may be added.

If the changes in the period are themselves variable, then the variations cannot be represented by this equation, and recourse to the sine or cosine functions becomes necessary. The equation will then assume the form,

$$T_1 = T_0 + PE + c \sin (bE + d),$$

c, b and d being constants to be determined from the observations.

The star 4826, R *Hydræ*, shows changes of both a secular and a periodic nature, and its observed variations can be represented by the equation,

$$T_1 = T_0 + 496^{d}.91\,E - 0^{d}.2307\,E^2 - 0^{d}.001276\,E^3 + 80^{d}.5 \sin (4^{\circ}.3\,E + 353^{\circ}.7).$$

It is highly probable that all the stars of this class will show variations of period of either a secular or a periodic character or both, but the vast majority of them have not been observed sufficiently to determine the form of these variations, and until further observations are obtained can be represented only by a mean period.

Amount of Variation in Brightness. The amount of change in variables of this class is usually from five to eight magnitudes, although in some the change is small, that of 7754, W *Cygni*, being from four-tenths to six-tenths of a magnitude in a period of one hundred and twenty-six days. The amount of change in any particular star is not constant, and the range between different maxima and different minima usually is about a magnitude.

For 513, R *Piscium*, the range at maximum, according to CHANDLER'S Catalogue, is from $7^{\rm m}.0$ to $8^{\rm m}.8$ and I have observed two minima of the star, 1891, January 8 at $16^{\rm m}.2$ and 1891, December 8 at $14^{\rm m}.0$, a range of over two magnitudes.

Of 466, U *Piscium*, I have observed three maxima and three minima, as follows:

Maxima.	Minima.
1889, Dec. 17, 9.5 mag.	1890, Sept. 7, 14.5 mag.
1890, Nov. 24, 9.4 "	1891, Feb. 22, 14.7 "
1891, Nov. 8, 9.4 "	1892, Feb. 9, 14.7 "

These show a range of but one-tenth of a magnitude at maximum and of two-tenths at minimum. Both of these illustrations are extreme cases.

FORM OF LIGHT CURVE. The light curves of this class of variables are all alike in general form, but differ somewhat in particulars. Some have flat maxima, and others sharp ones; some have flat maxima and sharp minima, or *vice versa*. The curve of any particular star is not always the same, for one maximum may be flat and the next one sharp. In nearly all the rise from minimum is more rapid than the fall from maximum, and it has been found that the ratio of these two parts of the period is, in general, five to six. The above points are illustrated by the curves in the plate, taken from my own observations.

The curve of 466 is very regular, and illustrates the relation of the two parts of the curve, the time from minimum to maximum being seventy-eight days, and from maximum to minimum ninety days, a ratio which agrees closely with that given above.

The curve of 1717 is somewhat irregular, the first maximum being very flat and the second one rather sharp.

In a large number of the stars of this class there is a tendency for the curve to flatten out after passing the maximum, and this tendency in some cases even goes so far as to result in a secondary maximum, as is illustrated by Figure III.

COLOR. Mr. CHANDLER has determined the color of a large number of variable stars, and the result of his work shows some important facts. Nearly all variables of the long period class are of a red color, and it was this fact that led to a more detailed investigation. The colors of the stars are denoted by the numbers from zero to ten, the meaning of which can be explained best by the following quotation, taken from CHANDLER'S Catalogue of Variable Stars, page 3: "The redness is expressed to tenths of a degree of an arbitrary decimal scale, the zero of which corresponds to white light, and the other limit, ten, to the most intense shade of red of which we have cognizance in the heavens, exemplified by such stars as S *Cephei*, V *Cygni*, and R *Leporis*. As nearly as the intermediate degrees of this imaginary scale can be verbally defined, 1 corresponds to the slightest perceptible admixture of yellow with the white; 2 to a yellow; 3 to yellowish orange; 4 to a full orange or orange red; and 5 to 10 to increasing shades of intensity up to the limit described."

From the Catalogue I have taken all the long period variables of which Mr. CHANDLER has determined the redness and tabulated them in the following table. In the third column is given the mean redness of the stars whose periods lie between the limits expressed in the first column. In the fourth column is the redness graphically adjusted, and in the second column is given the number of stars upon which the mean depends.

Period.—Days.	Number.	Redness.	Adj. Redness.
50—100	3	1.3	1.3
100—150	3	1.4	1.5
150—200	7	2.2	1.8
200—250	8	2.1	2.3
250—300	16	3.1	2.9
300—350	25	3.5	3.7
350—400	17	4.8	4.8
400—450	11	6.3	6.2
450—500	5	7.6	7.8
500—550	0		
550—600	0		
600—650	1	6.7	
650—700	0		
700—750	0		

Here is shown a certain and gradual increase of redness with the increase of period, and other observers have found this law to be true. Variables of the other classes show a tendency to hold to the same law, for short period ones of both types are nearly all of an intense white color. In a general way, then, the redness of a variable is a function of the length of the period, but what this relation is and why it exists has not been determined. It is a fact, however, that cannot be neglected in the formation of a theory to explain stellar variability.

SPECTRUM. Most of these variables have spectra that belong to Type III, stars of red color and strongly marked absorption bands. There has been but very little systematic work done in this direction, although it is a rich field for investigation in the study of variable star phenomena. My opportunities have not been such as to enable me to study this branch of the subject, and I shall therefore pass over it without discussion.

CAUSES OF VARIABILITY. In the foregoing discussion of the Length of Period, Variation of Period, Amount of Variation in Brightness, Form of Light Curve, Color and Spectrum, many peculiarities of this class of variables have been found, and in all respects there appears a lack of perfect uniformity.

The magnitude is variable, the period is variable, the amount of change is variable, the manner of change is variable, and even sometimes the color and spectrum are variable. The first test, then, for any theory advanced to explain this type of stellar variability is to see if under it the observed peculiarities would be possible. If they would not, then the theory may be dismissed without consideration. Numerous theories have been put forward to explain these phenomena, and I will now consider some of the most important ones.

ECLIPSE THEORY. This theory, that the diminution of light in a star is caused by the revolution of a satellite (usually dark) around the primary star in a plane passing through the earth, is the true one for the explanation of the cause of variability in short period stars of the *Algol* type. But it is plain to be seen that this theory will not explain the variability in stars of long period, for, under the conditions of this theory, the light of the star must remain constant for at least half the revolution of the satellite, or half the period of the star, and this is the case in no other stars except variables of the *Algol* type.

AXIAL ROTATION. It has been supposed that variable stars may be brighter upon one side than upon the other, and that, by rotation, the bright and dark sides are alternately turned toward the earth.

This might explain a very small variation, but it is almost impossible to conceive of a star one side of which is two or three thousand times as bright as the other. Under such conditions, also, it would be natural to expect much more of uniformity than is actually observed. For instance, under this theory, it is impossible to explain the fact that the rise from minimum is quicker than the fall from maximum except by assuming highly improbable conditions. Again, too, it has been found recently that in a few of these stars bright lines appear in the spectra as the star approaches maximum, and this seems to indicate that the variability is associated closely with luminous changes in the stellar atmospheres. We may dismiss this theory, then, as entirely inadequate to explain the observed phenomena.

TIDE THEORY. Several German astronomers have attempted to explain the phenomena of variability through the tide influence of satellites. From the character of the spectra it is inferred that these variables possess highly absorptive atmospheres and the tide theory supposes that, as the satellite passes periastron, an immense atmospheric tide is produced, such as to largely increase the absorption and thus cause a diminution of brightness. Such a theory appears plausible enough, but I have been unable to determine how the light curves that are actually found could be produced in that manner. If we suppose the orbit of the satellite to be circular, or approximately so, and the plane of the orbit to pass through or near the earth, then with every revolution of the satellite the star would pass through two maxima and two minima with equal intervals between. But, as remarked before, it is almost an invariable rule that the interval from minimum to maximum is shorter than the interval from maximum to minimum.

It seems then that the observed phenomena cannot be explained on the supposition of a circular orbit. If, on the other hand, as is more likely to be the case, we assume the orbit to be eccentric, then the intervals would be unequal, but it would as often happen the interval from maximum to minimum would be shorter than the interval from minimum to maximum as *vice versa.* This appears to me to be a fatal objection to the tide theory, as a general explanation of the phenomena under consideration. The spectroscopic evidence, also, is no more favorable to the tide theory than to the axial rotation theory.

SPOT THEORY. It was long ago suggested that the variability of stars might be caused by disturbances similar to those occurring on the surface of the sun. There is a very marked resemblance between the curves of sunspot frequency and of long period variables. They are not only of the same general form, but they are marked by much the same kind of irregularities. Both are steeper in ascent than in descent; both show accelerated or retarded maxima and maxima of unequal intensities; both may show secondary maxima in the descent. In the curves representing these phenomena a maximum of spots on the sun corresponds to a maximum of light in the star and not *vice versa*, as might be supposed. As in some variables the apparition of bright lines has been detected at maximum, so in the sun the emissive intensity of the corona probably increases with the growth of spots. All these marked similarities lead one to infer common causes for the phenomena. There is one marked difference, however. In long period variables the mean change of brightness is about six magnitudes, while in the sun the change of brightness due to spots, tremendous as these disturbances are, could not possibly produce a change of more than a small fraction of a magnitude.

In respect to the spectra also there is a difference. The sun belongs to Type II, continuous spectra with narrow dark lines, while almost all the long period variables belong to Type III, red stars with strong and broad absorption bands. It is now generally believed that sunspots are caused by the downfall upon the sun's photosphere of cooled matter previously ejected, but it is almost impossible for us to conceive of a raining of matter on a star sufficiently great to produce a one or two thousand fold increase of brilliancy. This may be a true theory of stellar variability, but it cannot yet be accepted as such.

COLLISION THEORY. Mr. LOCKYER, in connection with his *Meteoritic Hypothesis*, has propounded a collision theory of stellar variability. The part of it that applies to the variables now under consideration is briefly as follows: These stars are not compact bodies like the earth or sun, but are swarms of meteorites, each attended by a satellite swarm revolving in a very eccentric orbit. The periastron distance is so small that when the satellite swarm reaches that part of its orbit the two bodies mingle to some extent, thus producing collisions and a consequent increase of light. As the satellite moves away from periastron the collisions become less numerous and the light of the star dies away. Thus the minimum brightness is the normal state and the maximum abnormal. Different types of variation can be illustrated by the diagrams.

In Fig. IV the satellite goes through the midst of the primary and at apastron is entirely free from the primary, which would produce a faint minimum with a large range to maximum. In Fig. V the satellite does not pass through the central part of the primary, so that the range of brightness would not be so large. In Fig. VI the satellite is never free from the primary, so that the minimum would be bright and the range to maximum small. And so by variations in the densities of the swarms, in the eccentricity and length of the orbit, in the positions of periastron and apastron, it is possible to explain any observed range in brightness or length in period.

If the star has a secondary maximum it is but necessary to suppose two satellite swarms rather than one. Irregularities in the occurrence of maxima and minima are explained by the supposition that there are satellite swarms which do not enter the primary, or are always within it, but whose attraction is sufficient to accelerate or retard the satellite swarm that does enter the primary.

As before stated, it is an observed fact that the rise from minimum is considerably more rapid than the decline from maximum ; this we at once see would be one of the necessary conditions of the collision theory.

Again, the brightness of a single star is not the same at every maximum, and this not only would be possible but highly probable under the collision theory. The spectra lend further support to this theory. The appearance of bright hydrogen lines and carbon flutings at the maxima of some of these stars indicates a real access of incandescence rather than a clearing away of atmospheric clouds or absorption vapors. The theory has the further advantage of explaining temporary stars in the same manner as variables of long period, and the spectra of these two classes are so much alike as almost to preclude the possibility of their being due to different causes. The recent discovery that the new star in *Auriga* was really composed of at least two bodies, lends further support to the collision theory.

Objections have been urged against this theory, the nature of which can be seen from the following quotation :*

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* MISS CLERKE'S *System of the Stars*, page 124.

"But the objection inevitably arises that this state of things could not long subsist. Even if set on foot, it would prove transient. By mechanical necessity, the satellite-swarm should speedily become extended into a ring, with, of course, complete effacement of variability. Thus each maximum of a star like *Mira*, if produced in the way supposed, would be feebler and more prolonged than its predecessor, until maxima and minima were brought to the same uniform level."[1]

Without doubt the continuance of collisions would *sometime* use up the satellite-swarm. But none of the variable stars have been known more than a few hundred years, and from what we know of the magnitude of sidereal bodies, and the time required for the evolution of the heavens, we are fully warranted in supposing that a few hundred years would make no perceptible difference in these stars. The other objection can be answered by an illustration from the solar system. The *Leonid* and *Andromede* meteors have been known much longer than any variable star, and they are as yet very far from being extended into rings.

The collision theory is the best one yet advanced to explain the observed phenomena. There are no serious objections to it as a theory, and any degree of regularity or irregularity can be explained by it without extravagant suppositions. It yet remains, however, to be proved that these stars are really meteoritic swarms, as Mr. LOCKYER states.

CONCLUSION. The *Eclipse Theory* is no longer advanced to explain the phenomena of long period variables.

The *Axial Rotation Theory* might explain a small variation in particular cases, but is entirely inadequate as a general explanation.

The *Tide Theory* is inconsistent with observed peculiarities, and hence cannot be accepted.

The *Spot Theory* may be a true one, but cannot yet be accepted as such.

The *Collision Theory* explains most satisfactorily the observed phenomena, but cannot be accepted as a true theory until further proof is furnished of the fundamental principles upon which it rests.

Investigations thus far have established the following facts: — That in the changes of variables of long period perfect uniformity is entirely lacking; that periods of about a year largely predominate; that the rise from minimum is more rapid than the fall from maximum; that an unusual proportion of red stars are variable, and that nearly all variables of long period are red; that the redness increases with the length of the period; that the spectra of nearly all are marked with broad and strong absorption bands; that in a few bright hydrogen lines and carbon flutings appear in the spectrum as the star approaches maximum.

From these facts it is highly probable that the variations in brightness are produced by luminous changes in the stellar atmospheres, and that these changes are brought about in some way by the influence of planetary, meteoric or cometary attendants.

But the time has not yet come to formulate with certainty the causes of variability of stars in this class. A large amount of work, both of a spectroscopic and telescopic nature, must first be done in order to learn more of the physical constitution of these stars, and of the peculiar laws under which their variations take place.

My observations referred to in this paper were made with the 15.5-inch equatorial telescope of the Washburn Observatory, at Madison, Wisconsin, between November, 1889, and July, 1892.

OBSERVATIONS OF THE OCCULTATIONS OF *MARS* AND *JUPITER*.

1892, SEPTEMBER 3 AND SEPTEMBER 9.

BY PROFESSOR J. M. TAYLOR.

OBSERVATORY OF THE UNIVERSITY OF WASHINGTON,
SEATTLE, WASH., September 13, 1892.

I send you the result of my observations of the occultations of *Mars* and *Jupiter*. I had no means at hand to determine my watch correction, but set it carefully by a regulator keeping Pacific standard time.

SATURDAY, September 3, 1892.

Observation of the Occultation of Mars by the Moon.

Immersion	First contact..	$9^h\ 27^m\ 15^s$.	P. S. time.
	Mars hidden..	$9^h\ 28^m\ 21^s$.	" "
Emersion	First sight....	$10^h\ 25^m\ 26^s$.	P. S. time.
	Full view.....	$10^h\ 26^m\ 21^s$.	" "